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The spectral transmittance has been studied with sinusoidal phase transmission gratings with 600 lines per nm and of varying groove depths from 637nm to 776nm in order to obtain minimum optical transmission in the wavelength range of 500nm to 1000nm. All the gratings were formed on photo-resist materials on glass substrates using a holographic technique. A high degree of attenuation of the zero order beam over a small wavelength range is attainable with a single sinusoidal transmission grating of an appropriate groove depth, λmin at which the transmittance is minimum, being proportional to the magnitude of the groove depth. A superposition of two crossed gratings of two dissimilar groove depths either on two different glass substrate or on a single substrate can provide a very low optical transmittance in the band 400-1000nm although the visibility through such a system is poor.

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Abstract

The present work is primarily concerned with the investigation of the spectral transmittance of sinusoidal phase transmission gratings of coherent radiations in order to obtain minimum transmission in the wavelength range of ~ 0.5 micron to 1 micron. The zero ordertransmittance of fourteen sinusoidal transmission gratings with 600 lines per mm have been measured. All the gratings were formed on photo-resist materials on glass substiates using a holographic technique. Ten gratings of varying groove depths in the range of ~ 637nm to 776nm were provided by the National Physical Laboratory (NPL) of the United Kingdom. NPL also produced two further gratings in which the two sinusoidal corrugations were superimposed (i.e. 90^{0} to each other, the crossed grating), on a single glass substrate, the effective groove depth being ~ 896nm. The remaining two gratings of groove depth ~ 537nm were obtained from the Optometrics (U.K.) Limited.

The transmission spectrum was found to be a function of the groove depth only, the diffraction angle being determined by the grating period. A high degree attenuation of the zero order beam over a small wavelength region is attainable with a single sinusoidal transmission grating of appropriate groove depth. The deeper the peak to peak amplitude of the sinusoidal profile is, the higher is the value of λ_{min}, at which the transmittance is minimum.

The gratings can be combined by linear superposition of their characteristics. Using two separate gratings of dissimilar groove depths of 637nm and 776nm and with profiles at right angels to each other, a maximum of 6% transmittance was obtained for the zero order beam over a spectral range of 400-1000nm, λ_{min} being at ~ 565nm. A crossed two groove profiles normal to each other) with a groove depth of ~ 896nm on a single substrate provided less than 1% transmittance at 500-680nm wavelength and the transmittance did not exceed 12% for the entire band of 400-1000nm.

The crossed gratings format described above, satisfied the required specification. However, the transmittance in the visible part of the spectrum, with deep groove depth, is very low.

1. Introduction

The objective of the present work has been a study of the behaviour of the deflection of coherent (laser) radiations in the wavelength range of 0.488 microns to 1.08 microns using sinusoidal transmission gratings as a function of groove depth. Furthermore, it was proposed to use a combination of two such photoresist gratings of appropriate groove depths in a manner than the plane of corrugation of one sinusoidal grating is perpendicular to the other in order to obtain a maximum attenuation of the zero order beam in the spectral range of 0.488 - 1.08 microns. It was also suggested that we were to seek the feasibility of fabricating two independent grooves, normal to each other on a single substrate and study the overall transmission response in the wavelength range, mentioned above.

2. Theory of Sinusoidal Transmission Grating

Figure 1 shows the general profile of the sinusoidal transmission phase grating. The grating corrugations have a period d and physical groove depth a′. A characteristic feature of the sinusoidal transmission grating is the low intensity of the even diffraction order m (m = 2, 4, 6 etc). This fact ensures their stability for multiple imaging applications [1]. The diffraction angle β is given by the familiar grating equation (see figure 1).

$$d \, \mathrm{Sin} \, \beta_m = m\lambda \qquad .....(1)$$

where λ is the wavelength of the incident coherent radiation. Note that the diffraction angle is dependent on the ratio λ/d only and not on the structure of the grating. The diffraction pattern produced by a sinusoidal transmission grating, however, depends on the actual profile of the grating. The wavefront is distorted (see figure 2) due to the velocities of the waves in the different media. The diffraction efficiency of a sinusoidal grating of refractive index n_g in air is given by [1-3].

$$D_m = \left[\left(\frac{1}{d} \right) \int_0^d \left\{ \exp 2\pi \, i \, s\,(x) \, (n_g - 1)/\lambda - \frac{mx}{d} \right\} dx \qquad .....(2)$$

where D is the diffraction efficiency. s(x) represents a relief function of the grating. The factor $^1/d$ provides a normalization.

With the sinusoidal gratings,

$$s(x) = \frac{a'}{2} \, \mathrm{Sin} \left(\frac{2\pi x}{d} \right) \qquad .....(3)$$

Substituting equation 3 in equation 2, we et [2, 3],

$$D_1 = J_1^2 \left[\pi \, a' \, (n_g - 1) \, \lambda \right] \qquad ....(4)$$

where J_1 is the first order Bessell function of the first kind. Thus the diffraction efficiency of a sinusoidal grating takes the form of a squared Bessel function. This function has been plotted in figure 3 for the zero and the first order beams.

3. Experimental

Ten sinusoidal (phase) gratings of different, but unspecified groove depths, formed on photo-resist (refractive index n_g = 1.64 at 634nm) on glass substrates n_s = 1.46 at 635nm) were provided by the National Physical Laboratories, (NPL), U.K. These gratings were produced by the NPL using a holographic technique.

The gratings specifications are as follows:

600 lines per mm sinusoidal photo resist gratings on 30mm diameter green plate glass with various groove depths from ~ 637 to 776 nm.

The actual groove depth a' was not specified by the NPL, but estimated in the present work.

The NPL also provided two holographically produced crossed sinusoidal (phase) diffraction gratings using similar photoresist and substrate materials, stated above, the groove period being again 600 lines per mm. the groove depths were unspecified. Figure 4 and 5 show schematically sections of single profile and crossed profile sinusoidal phase gratings.

Two other single profile holographically produced sinusoidal photoresist gratings (600 lines per mm) on 25.4 mm^2 glass plate were provided by Optometrics (UK) Ltd. The groove depths of these two gratings were again not specified by the manufacturer.

The transmission spectra of all these gratings were studied in our laboratories using a well focused microscope lamp (light source), a monochromator (Hilger and Watts) and a silcon photo detector (Anritsu Model ML9002A Power Meter with Model MA 9422A Sensor). A schematic diagram of the experimental arrangement is shown figure 6. Measurements of the transmission spectra were made over the range of wavelengths from 400nm to 1000nm in steps of 25nm using the calibrated monochrometer. The transmission spectral data for each grating were normalized with respect to the power spectrum of the light source in the same wavelength region.

4.0 Results & Discussion

4.1 Single Sinusoidal Transmission Gratings (NPL)

Figure 7 shows the power spectrum of the light source used in the present work. The normalized transmittance (%) spectra of the ten NPL sinusoidal gratings in the wavelength range of 400-1000 nm are shown in figures 8-17. It should be noted that the stated groove depth in figures 8-17 refer to the physical peak to peak value a', estimated from the spectral response in each case.

The optical peak to peak amplitude a is related to the physical peak to peak value a' of the groove thus,

$$a = a' \; (n_g - n_a) \qquad .....(5)$$

where n_g and n_a are the refractive indices of grating medium and air respectively. Thus, higher the difference in the refractive indices is, the smaller is the physical amplitude a' of the groove of the grating for a given response. This is an advantage, in general, as the quality of the profile tends to deteriorate with increasing depth during the fabrication of the grating. However, refractive indices of most epoxies, plastics and glasses are in the range 1.4 to 1.7, although special glasses with the refractive index of 2.4 do exist. It is, however, difficult to have deep etching with hard glass.

The groove depth may be estimated by assuming that the zero order transmittance to be zero at a wavelength where it is observed be a minimum. Thus we may write from equations 4 and 5,

$$0 = J_0^{\,2} \left[\pi a^1 \left(n_g - n_a \right) / \lambda \right] \qquad .....(6)$$

By a reference to a table of Bessel functions [4] the value of $J_0^{\,2}$ at which the transmittance is zero, is found to be 2.4. Equation 6 may be solved and with $N_g = 1.64$ and $n_a = 1$ and we get,

$$a^1 = 1.19 \; \lambda_{min} \qquad .....(7)$$

where λ_{min} is the wavelength at which minimum transmittance occurs. The magnitude of the physical peak to peak groove depth may be estimated from the experimental observation of λ at which the transmittance is a minimum (i.e., λ_{min}).

Using the above analysis a' - values of the ten NPL gratings were calculated from the λ_{min} - values in figures 8-17.

Table 1 and figure 18 show the behaviour of λ_{min} and the a' - values (peak to peak physical groove depth) from which it may be observed that a^1 - values need to be quite large for high values of λ_{min}. Indeed, it may be noticed from figure 17, that the grating no. 10 with a' - value of 776nm provides perhaps as good a spectral response as can be expected using a single sinusoidal phase grating. however, its transmittance in the wavelength range of the visible spectrum is quite small and a transmittance of 10-15% in wavelength range of 800-1000nm may also be unacceptably hazardous. These results thus show the limitations of the applications of single sinusoidal gratings to restrict the transmittance of harmful coherent radiations in a satisfactory manner, although over a narrow range of wavelength the sinusoidal gratings with appropriate groove depths would be a satisfactory and relatively inexpensive method for a protection against harmful radiation.

4.2 Groove Depth Determination by SEM Technique

The NPL were unable to provide information on the groove depths (a' - values). An attempt was made in our laboratories to measure the physical

peak to peak amplitude with a Scanning Electron Microscope (SEM) using a shadow graph technique in which the electron beam of the SEM was incident on a grating surface at an angle of 15^0. The shadow cast by the groove was then measured and the groove depth calculated. A typical SEM result of groove shadow casting is shown in figure 19 for the Grating no. 10 and the calculated groove depth from it appears to be ~ 830nm which is within 7% of the estimated value of a′ using the equation 7. It may thus be argued that equation 7 provides a reasonable estimate of the sinusoidal grating physical groove depth from an experimental determination of the λ_{min} value at which the transmittance is minimum.

4.3 Crossed Gratings On Different Substrates (NPL)

The transmittance through two superimposed grating system is the product of the two individual grating transmittances. For two crossed sinusoidal gratings of optical peak to peak amplitude a_1 and $_2$ the transmittance is given by [2],

$$T(\lambda) = J_0^2\left(\pi a_1/\lambda\right) J_0^2\left(\pi a_2/\lambda\right) \qquad .....(8)$$

where T(λ) is the transmittance, (i.e., zero order efficiency) and J_0 the Bessel function of zero order and first kind.

A crossed two grating system was investigated experimentally using (gratings Nos. 1 and 10 with a′ - values of 637nm and 776nm) with their corrugations crossed, i.e., mutually perpendicular), these two groove depths being the shallowest and the deepest respectively amongst the ten gratings provided by the NPL. The spectral response of this system is shown figure 20 from which it may be seen that the region of minimum transmittance has been extended in the wavelength range of 500nm to 1000nm with maximum transmittance not exceeding 6% at the two extreme ends. Thus although such a crossed grating system is quite effective in providing a wide and extremely low transmittance band, the visibility through the crossed grating system at optical frequencies remains very low.

4.4 Crossed Grating System On A Single Substrate (NPL)

The effects of the spectral cut off bandwidth with two crossed grating system may be achieved using a single two-dimensional phase grating (see figure 5) on one substrate. Two such photoresist and crossed gratings of unspecified groove depth values were provided (Gratings Nos. 11 and 12) by the NPL.

A preliminary examination of these two gratings (Nos. 11 and 12) showed that the optical plane of one or both axes on each grating was not coplaner with the substrate. Both gratings were found to have a first order diffraction angle β_1, of 22^0 in both cases, thus giving a grating period d, of 1.67μm or 600 lines per mm. The angle of doubly diffracted β_{11} beam was found to be 30^0, as expected. The transmission spectrum for the Grating No. 11 is shown in figure 21 from which it may be seen that λ_{min} is at 750nm (0.5% transmission), thus giving a profile depth a′ - value of 896nm and an optical amplitude a - value of 573 nm. It may also

be observed from figure 21 that the zeroth order transmittance does not exceed 10% in the wavelength range 450nm to 1000nm. The transmittance spectrum and the groove depth of the second NPL crossed grating (no. .12) were observed to be similar to that of the Grating No. 11. Both the crossed gratings show promise to meet our preliminary requirement although the transmittance (%) in the visible region of the spectrum remains again very low.

4.5 Optometrics Single Sinusoidal Gratings

The two identical gratings (Nos. 13 and 14) provided by the Optometrics (U.K.) Ltd are commercially available products with unspecified groove depth. Figure 22 shows the transmittance spectrum of Grating 13 which has a λ_{min} at 450nm (6% transmittance). This indicates a physical groove depth (a') of 537nm. Both the gratings (Nos. 13 and 14) have 600 lines per mm (d = 1.67μm). However, Grating No. 13 exhibited a lower transmittance than the Grating 14 which suggests that the former grating has a better sinusoidal profile, the result being closer to the theoretical case), than that of the latter grating. It became obvious that the two gratings provided by the Optometrics (U.K.) Ltd., could not produce the required rejection band because of their too shallow groove depth (a'). The manufacturers were unable to provide us with gratings possessing deeper groove depths.

Note: All fourteen gratings (twelve from NPL and two from Optometrics) were handed over to Dr. R.J. Shuford at the end of their transmittance study in our laboratories.

5. Conclusion

Present results indicate that it is possible to obtain a high degree of attenuation in the zero order beam for a small rejection band of wavelength using a sinusoidal photoresist phase transmission grating of appropriate values of the period (d - value) and the groove depth (a' - value).

The greater the groove depth is, the larger is the value of λ_{min} at which the transmittance of the coherent radiation is minimum. However, it becomes quite difficult to produce very deep groove depth on a photoresist by the holographic technique with good sinusoidal pattern and repeatability. Although both NPL and Optometrics were unwilling to provide a measure of the groove depths of their gratings, it appears that the technique of shadow casting, used in this work with a Scanning Electron Microscope in which the grating plane is held at a suitable tilt angle to the electron beam, provides a measure of the groove depth which is in reasonable agreement with the estimated value from the location of λ_{min} in the transmittance spectrum.

If the amplitude of the profiles are dissimilar, the range of wavelengths over which the incoming beam is attenuated is increased. By a suitable choice of two dissimilar groove amplitudes with two separate crossed gratings or crossed groove profiles on a single glass substrate a wide rejection band in the spectral range of ~ 500 to 1000nm may be obtained.

The results achieved in this work satisfy the specification which was required of us to fulfill. It should, however, be noted that the transmittance in the visible part of the spectral region is quite low for a crossed sinusoidal grating system.

6. References

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   Surface Relief Images for Colour Production
   Focal Press (London, New York), chapter 2, pp 10-29 (1980)

3. M.T. Gale
   Surface Relief Gratings for Zero Order Reconstruction
   Optical Communications, 18, pp 292-297 (1976)

4. H. Abramowitz & I.A. Stegun
   Handbook of Mathematical Functions, Dover (1988)

TABLE 1: Estimated values of physical groove depth a', of NPL Sinusoidal Gratings.

Grating No.	λ_{min} (nm) (experimentally determined)	$a' = 1.19\ \lambda_{min}$ (nm)
1	533	637
2	542	647
3	550	657
4	558	667
5	566	677
6	583	696
7	592	706
8	617	736
9	646	771
10	650	776

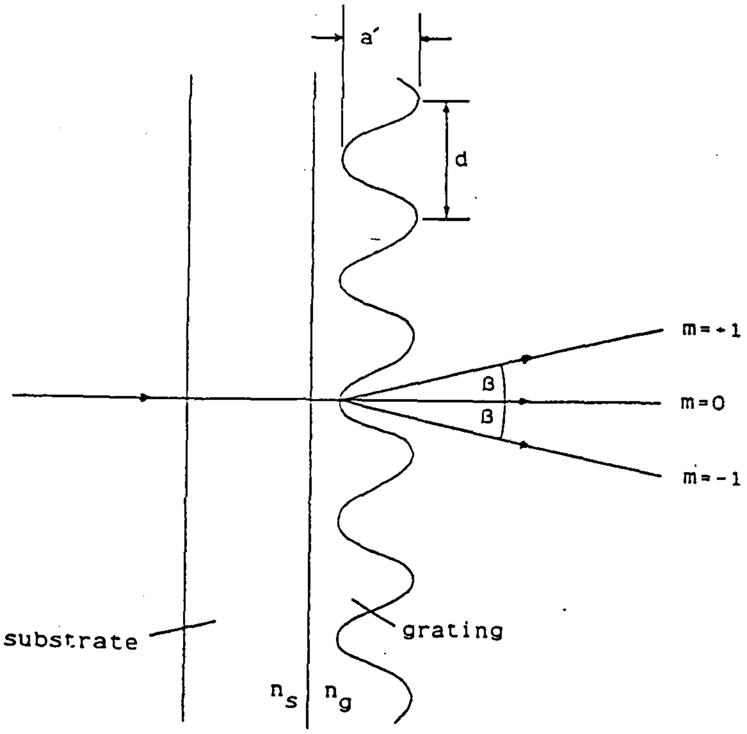

Figure 1. Sinusoidal Transmission Phase Grating

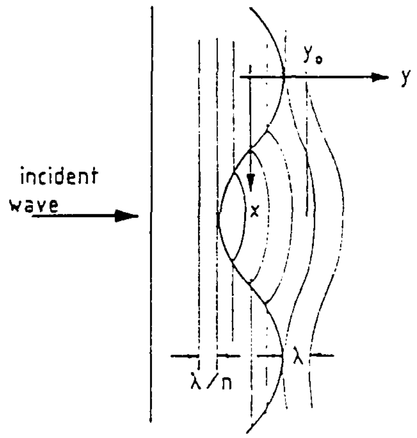

Figure 2. Distortion of plane wave due to grating profile.

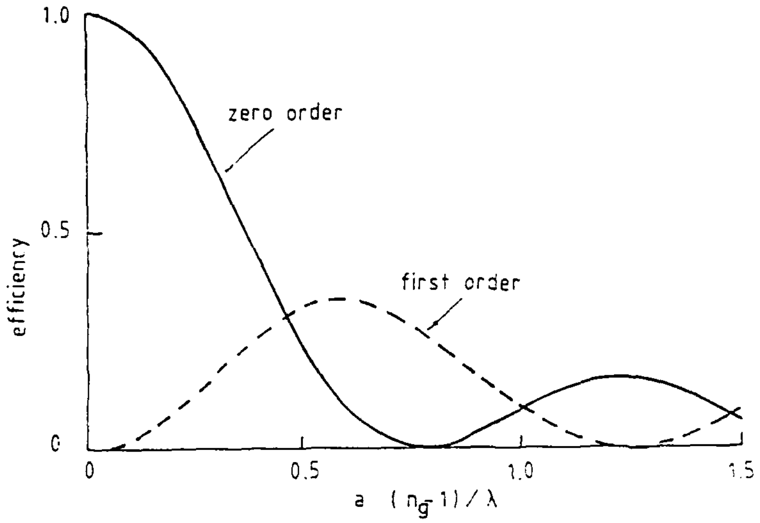

Figure 3. : Zero and first order diffraction efficiencies of a sine-wave phase grating (amplitude a', medium refractive index n_g) as calculated from Equation 4

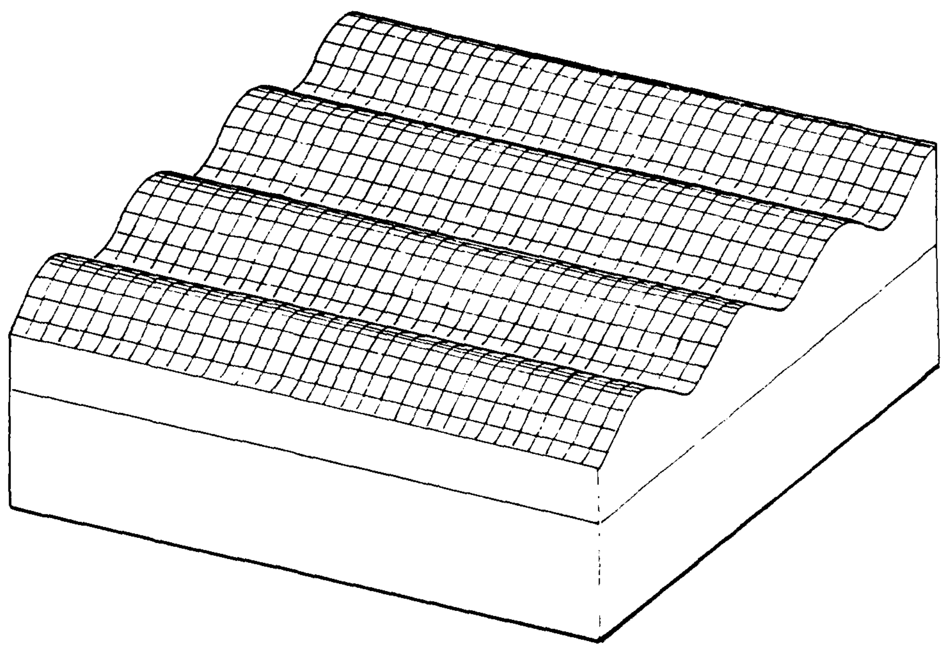

Figure 4. Section of a holographically produced , single profile, sinussoidal phase diffraction grating.

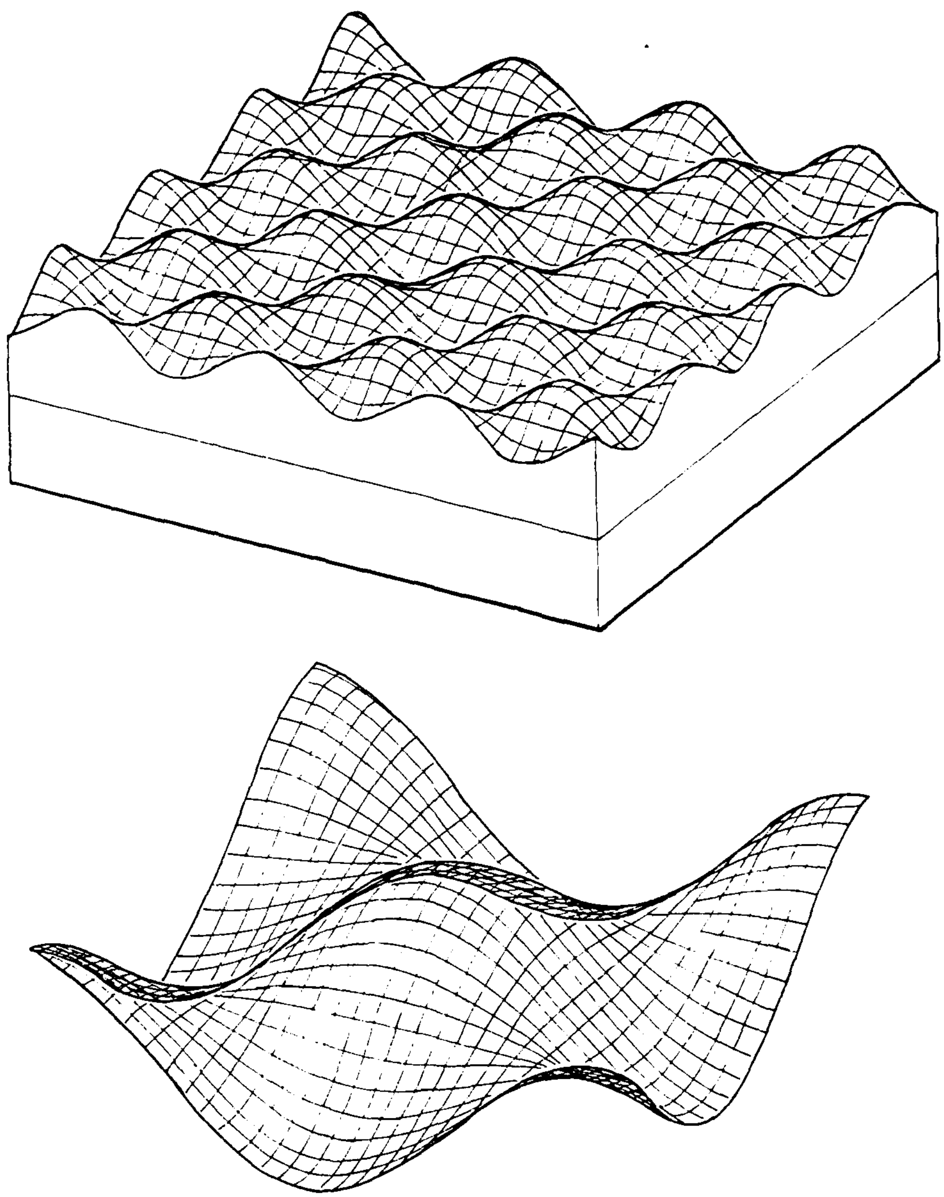

Figure 5. Two sections of a holographically produced, crossed profile, sinnusoidal phase diffraction grating.

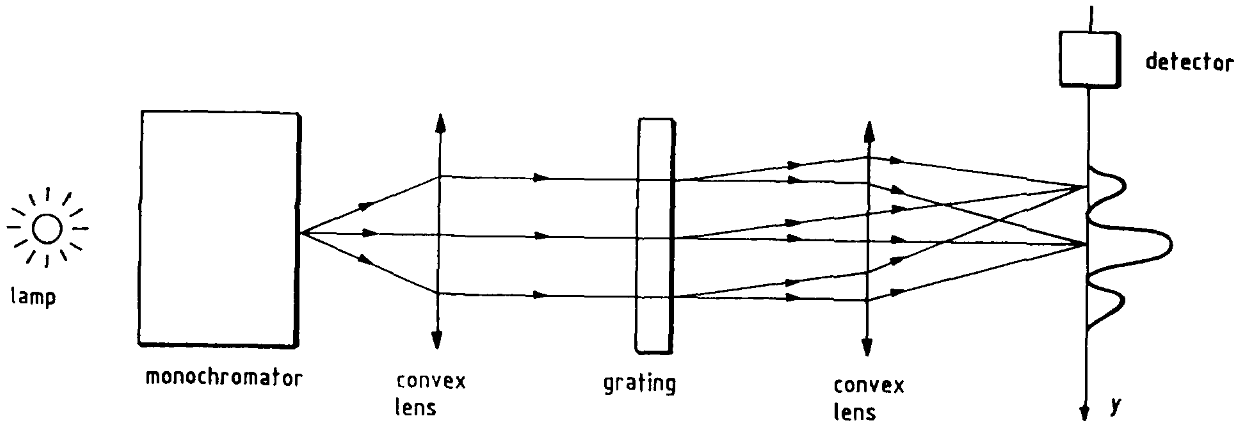

Figure 6. Wavelength response experimental arrangement.

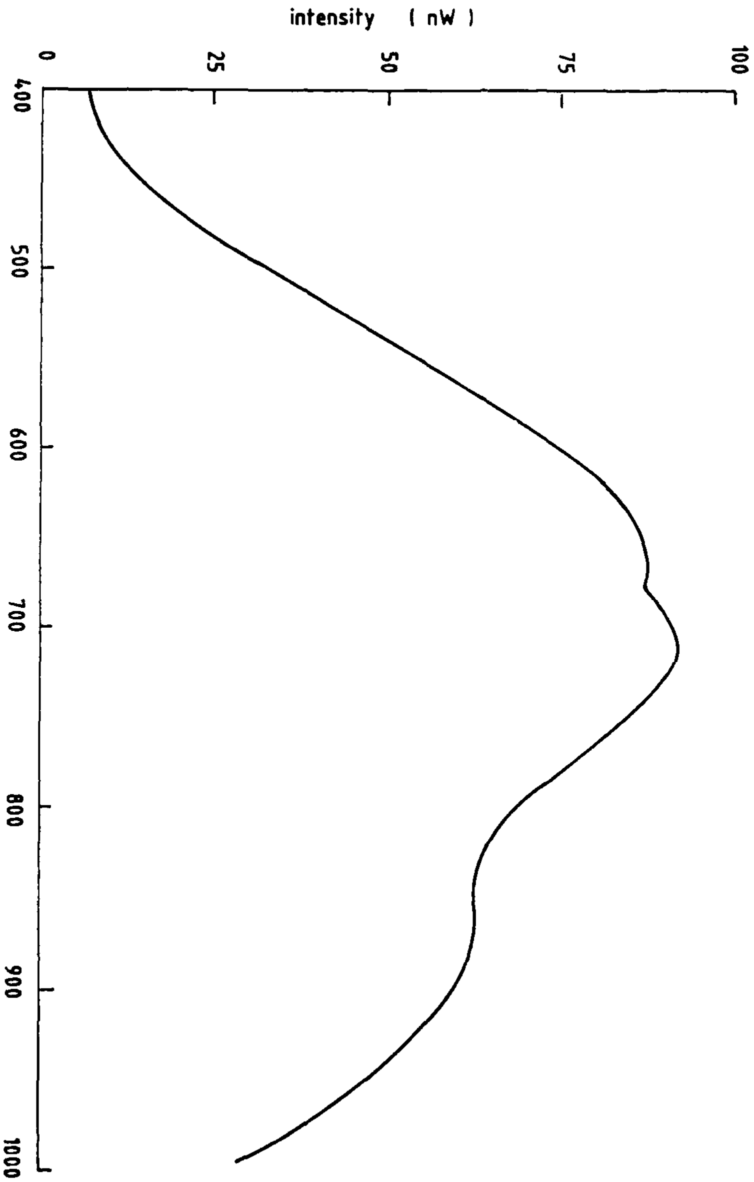

Figure 7 : Power spectrum of the light source.

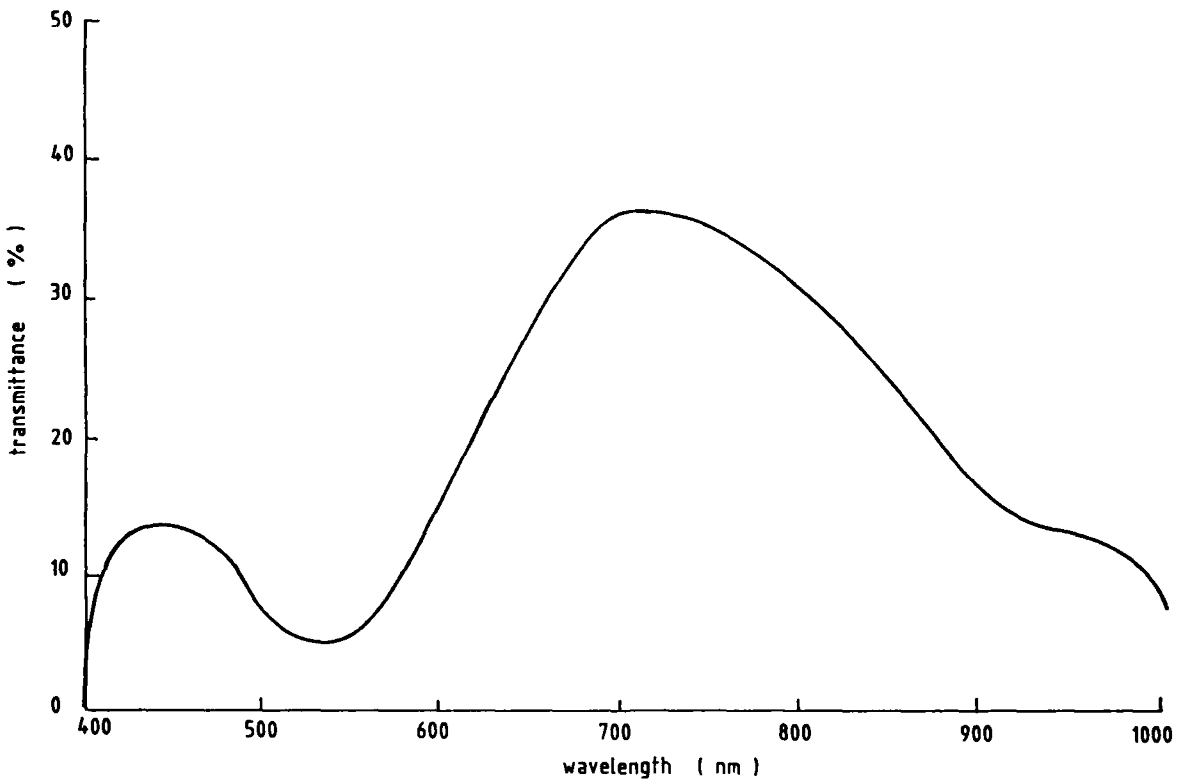

Figure 8. Normalized transmittance (%) / wavelength (nm) of grating 1 of groove depth 637 nm.

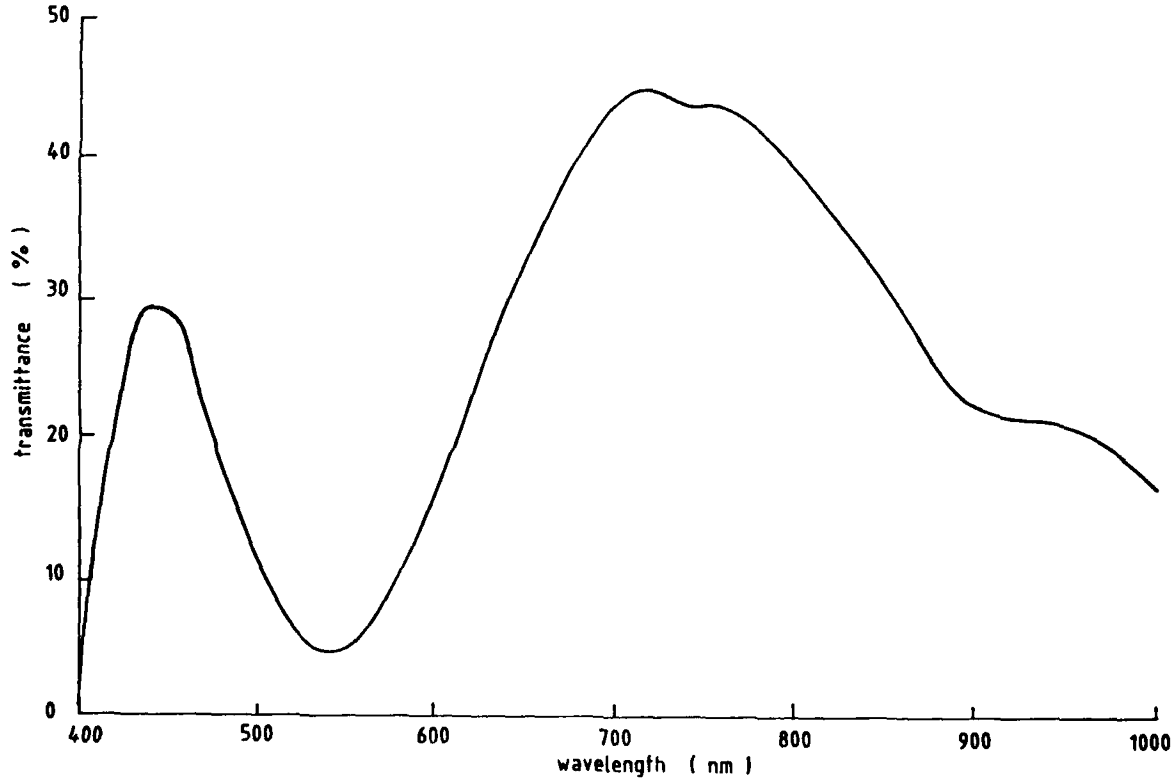

Figure 9. : Normalized transmittance (%) / wavelength (nm) of grating 2 of groove depth 647 nm .

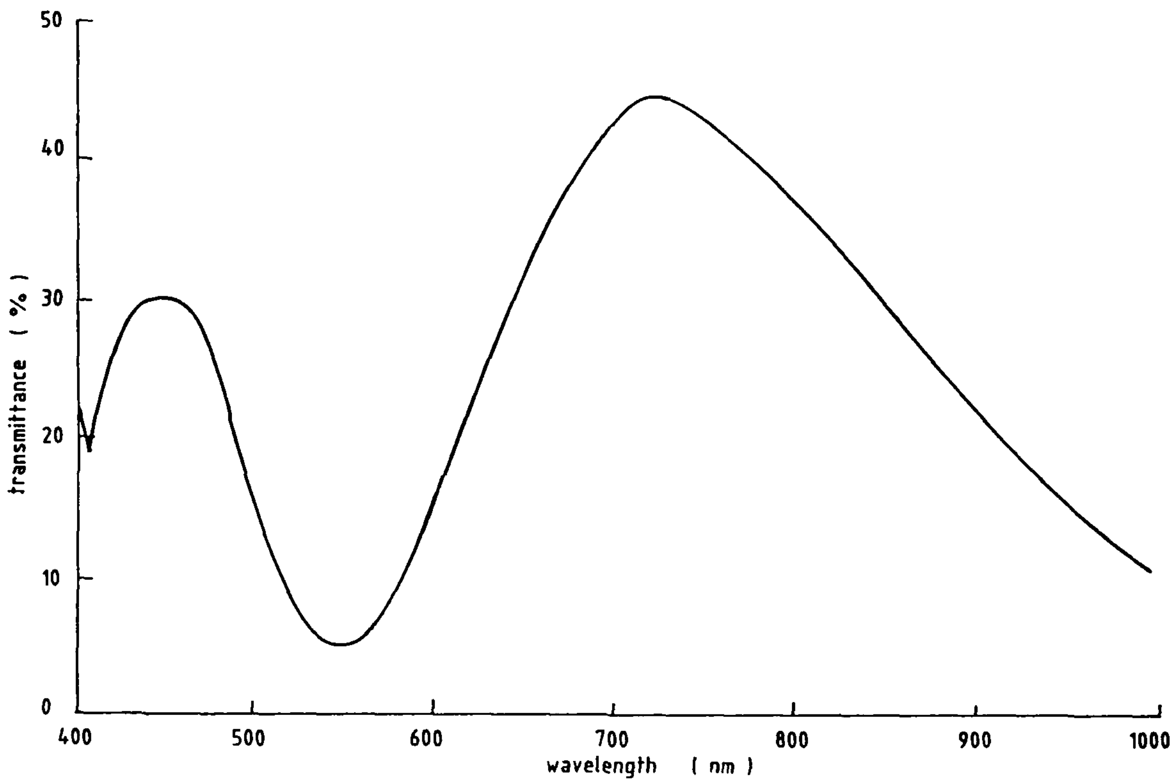

Figure 10. : Normalized transmittance (%) / wavelength (nm) of grating 3 of groove depth 657 nm .

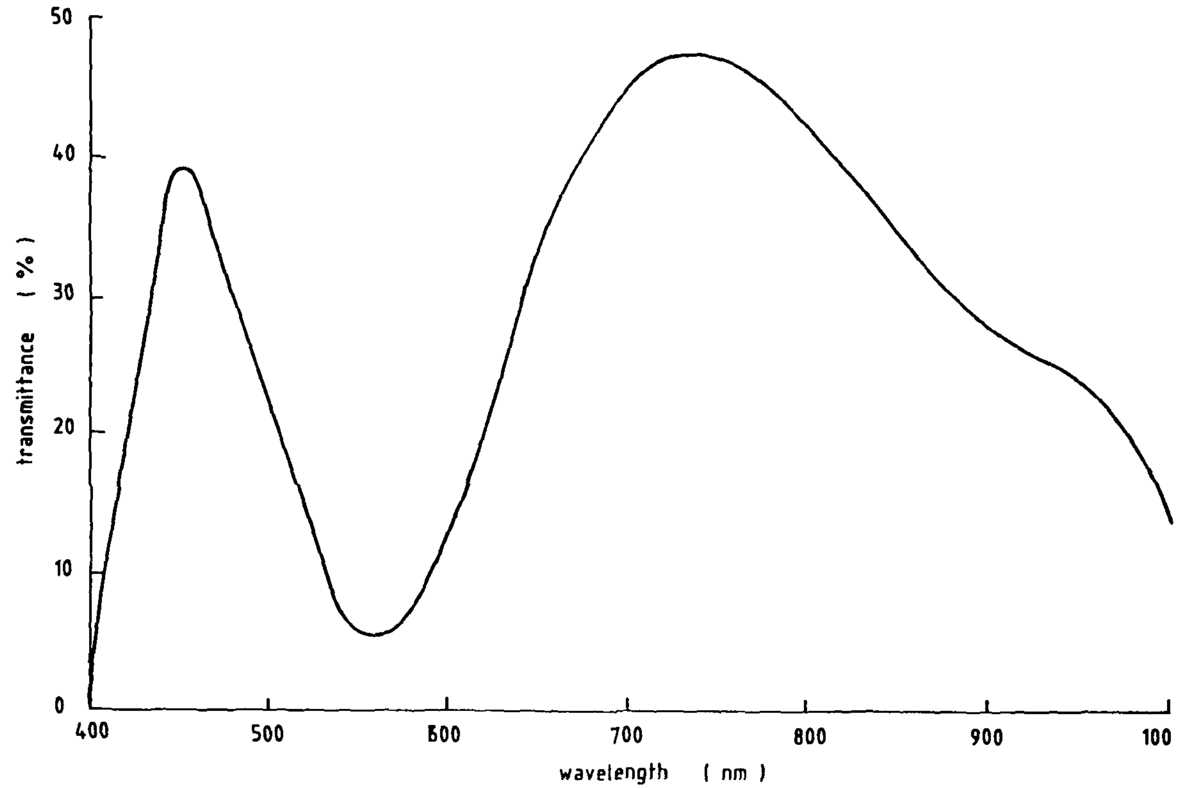

Figure 11. : Normalized transmittance (%) / wavelength (nm) of grating 4 of groove depth 667 nm.

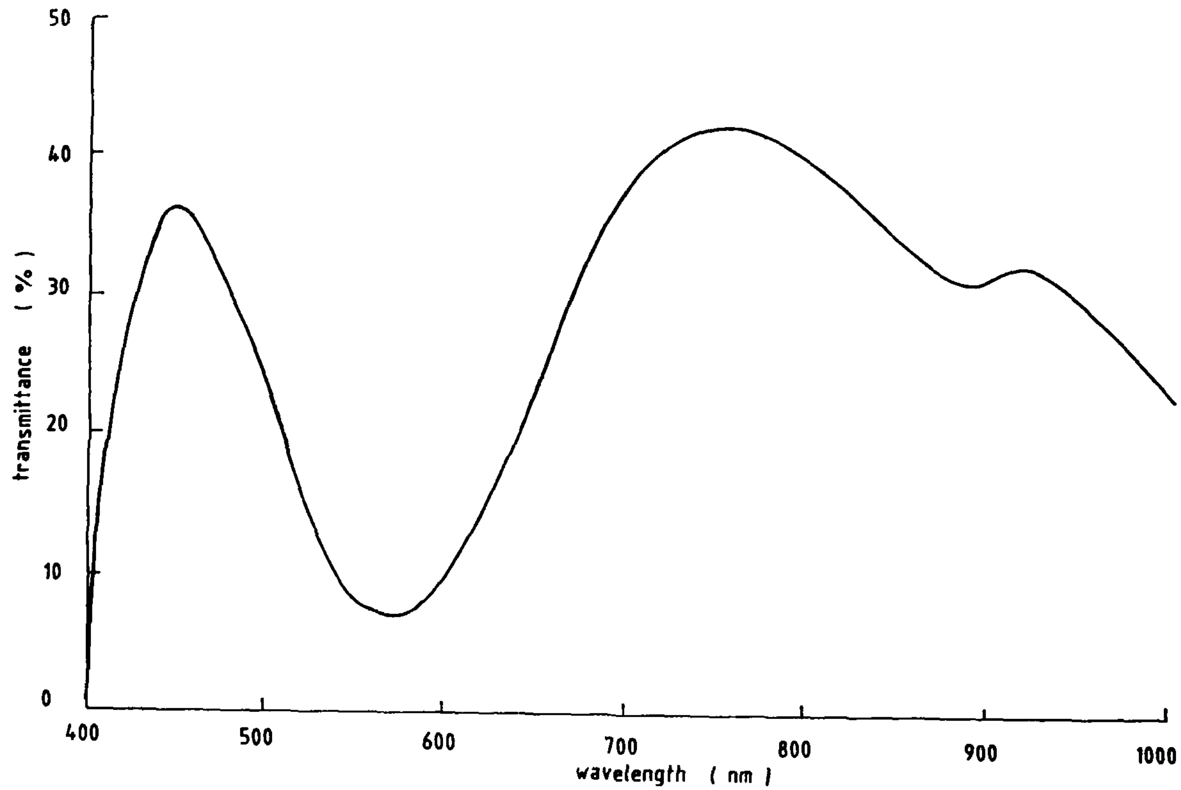

Figure 12. : Normalized transmittance (%) / wavelength (nm) of grating 5 of groove depth 677 nm.

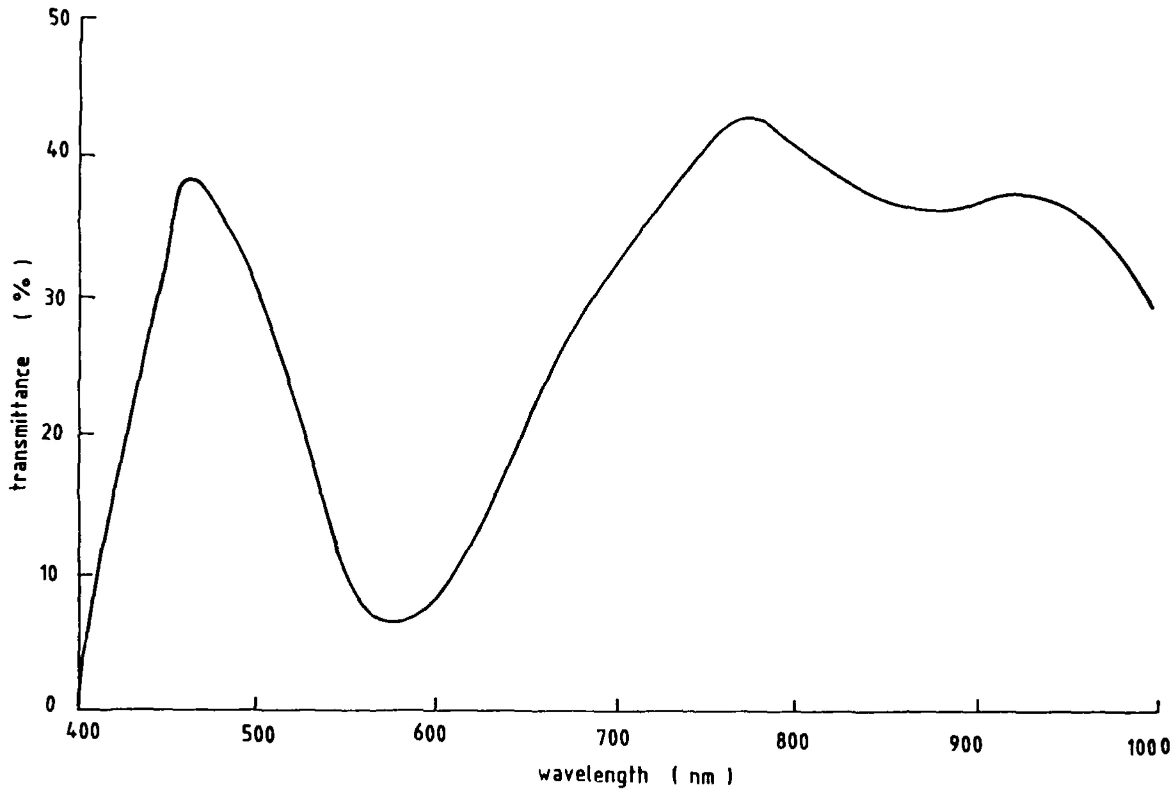

Figure 13. : Normalized transmittance (%) / wavelength (nm) of grating 6 of groove depth 696 nm .

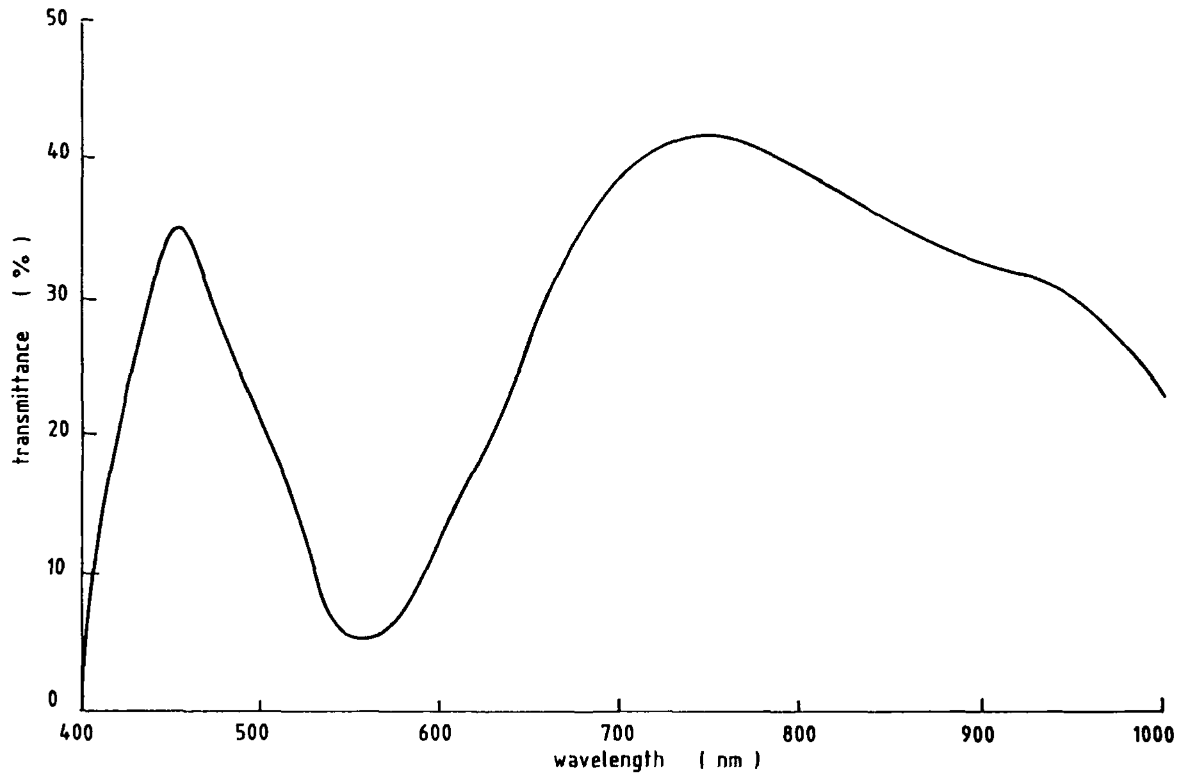

Figure 14. : Normalized transmittance (%) / wavelength (nm) of grating 7 of groove depth 706 nm.

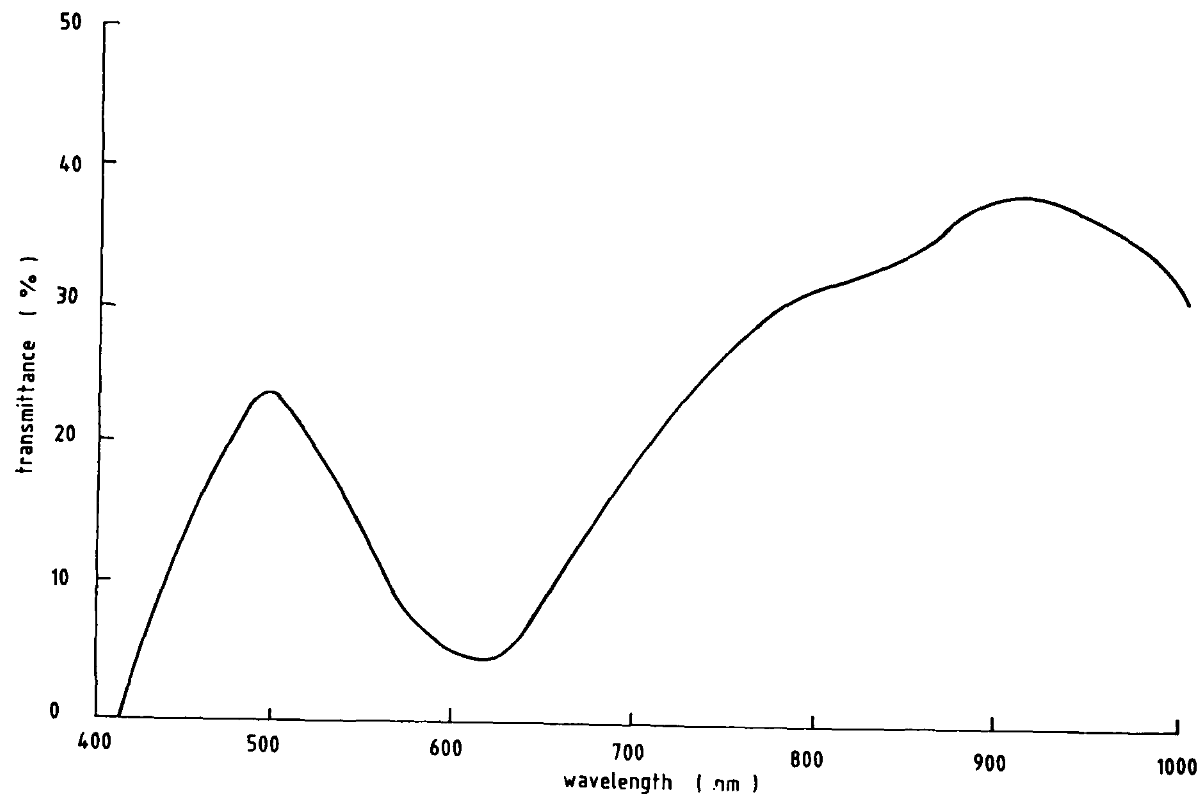

Figure 15. : Normalized transmittance (%) / wavelength (nm) of grating 8 of groove depth 737 nm.

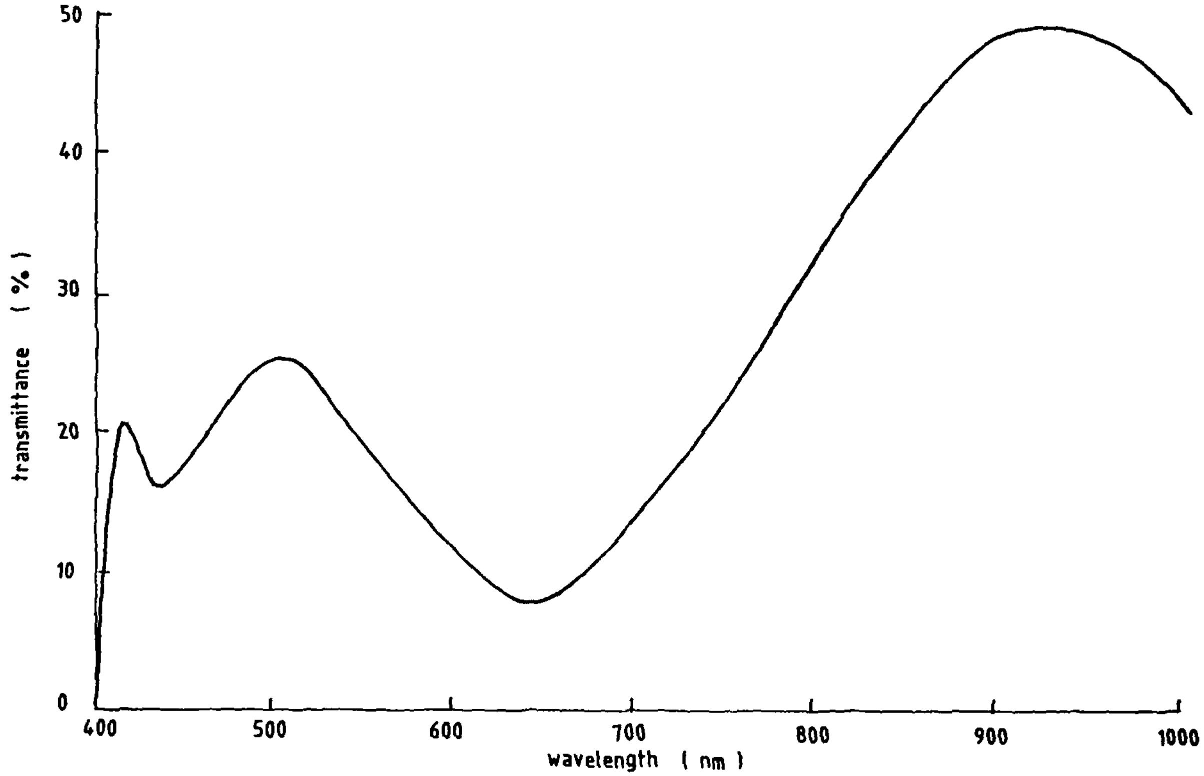

Figure 16. : Normalized transmittance (%) / wavelength (nm) of grating 9 of groove depth 771 nm.

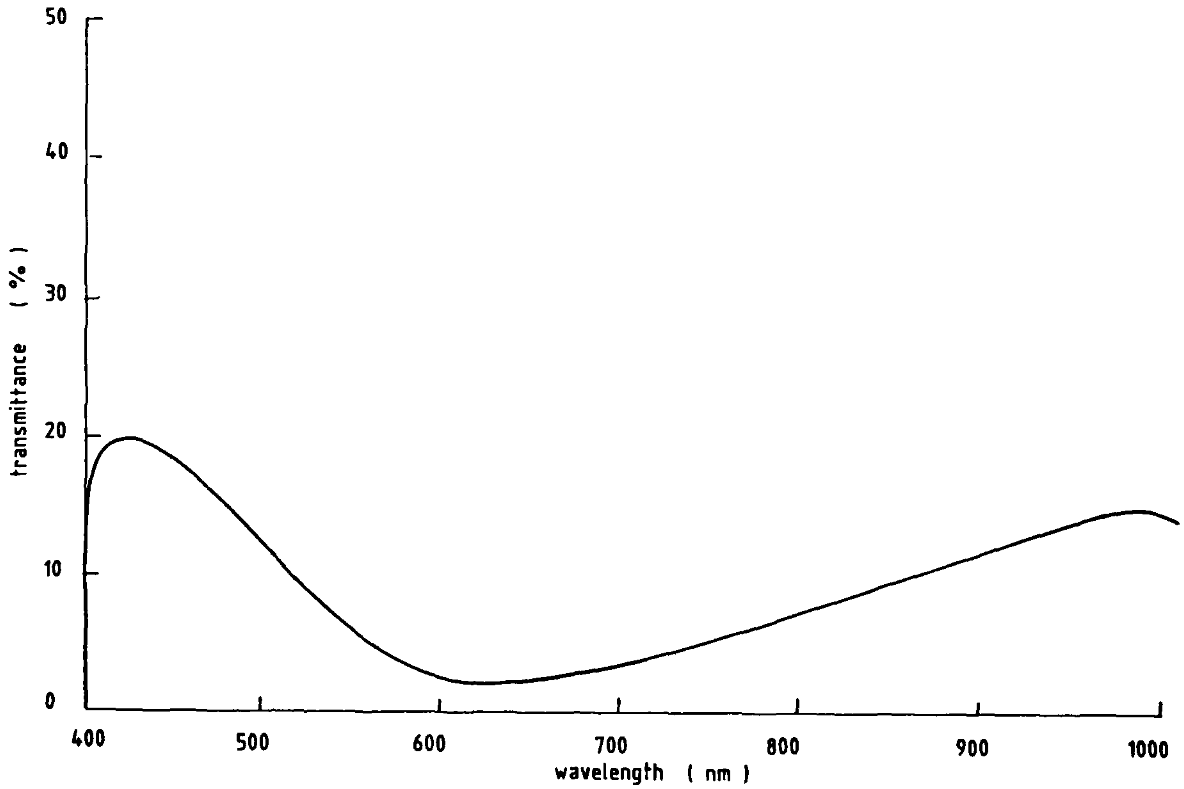

Figure 17. : Normalized transmittance (%) / wavelengtn (nm) of grating 10 of groove depth 776 nm.

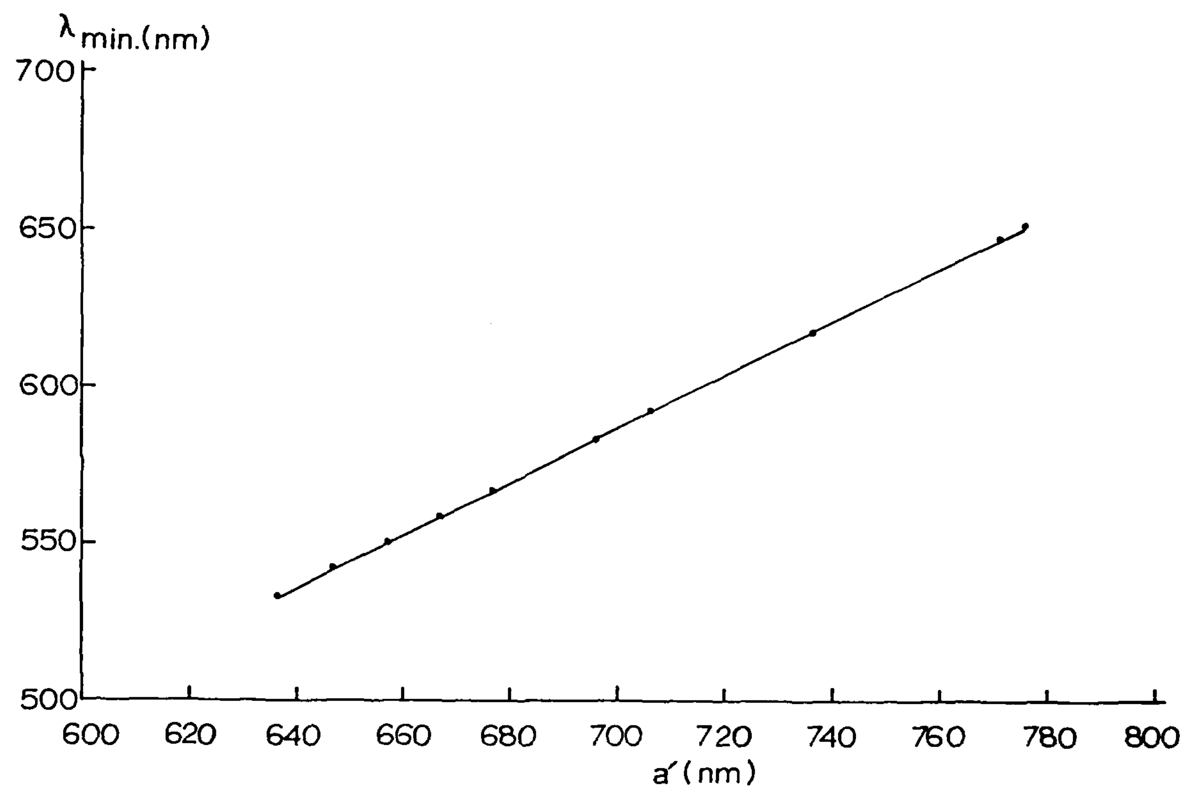

Fig 18. Behaviour of the physical groove depth a′ and λ_{min} at which a minimum transmittance occurs.

Calculated groove depth = a' = 830 nm.
from the shadow cast. (cf. estimated from equation 7 = 776nm.)

Fig.19. SEM Shadow casting in determining the groove depth of NPL grating 10.

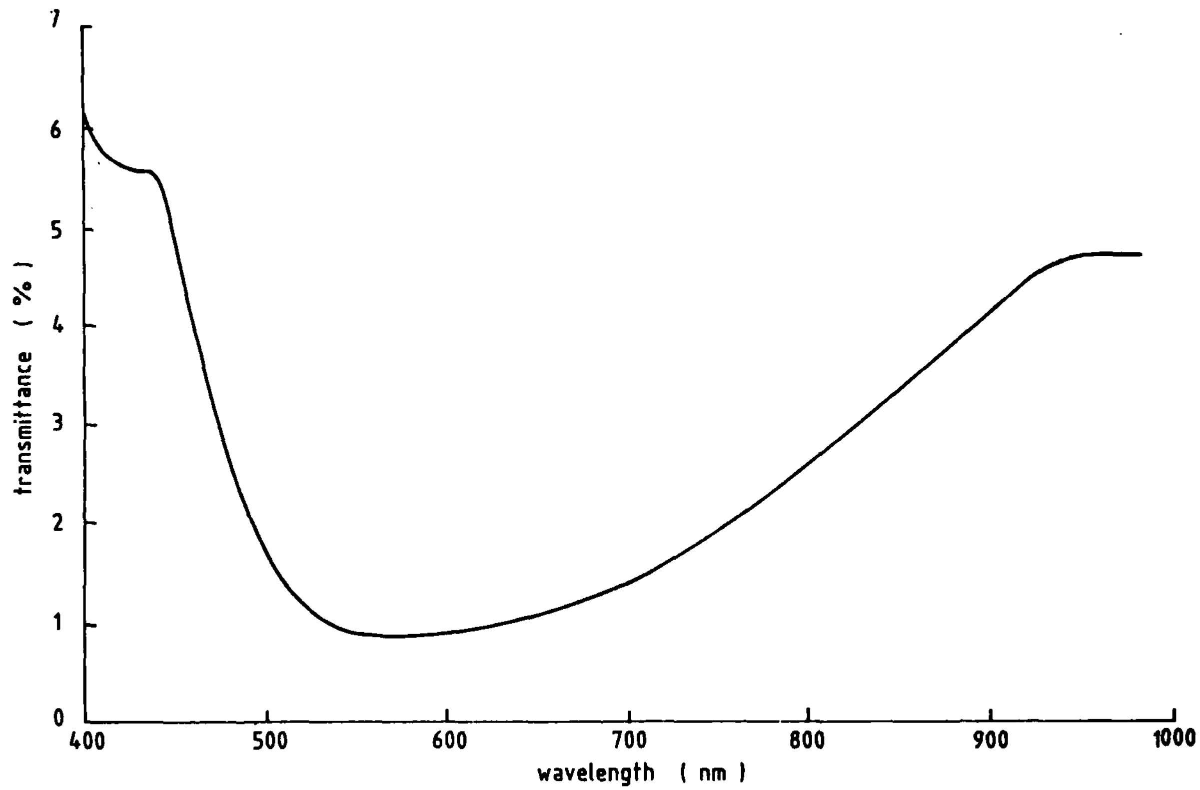

Figure 20. : Normalized transmittance (%) / wavelength (nm) for gratings 10 (776 nm groove depth) and 1 (637 nm groove depth) placed crosswise.

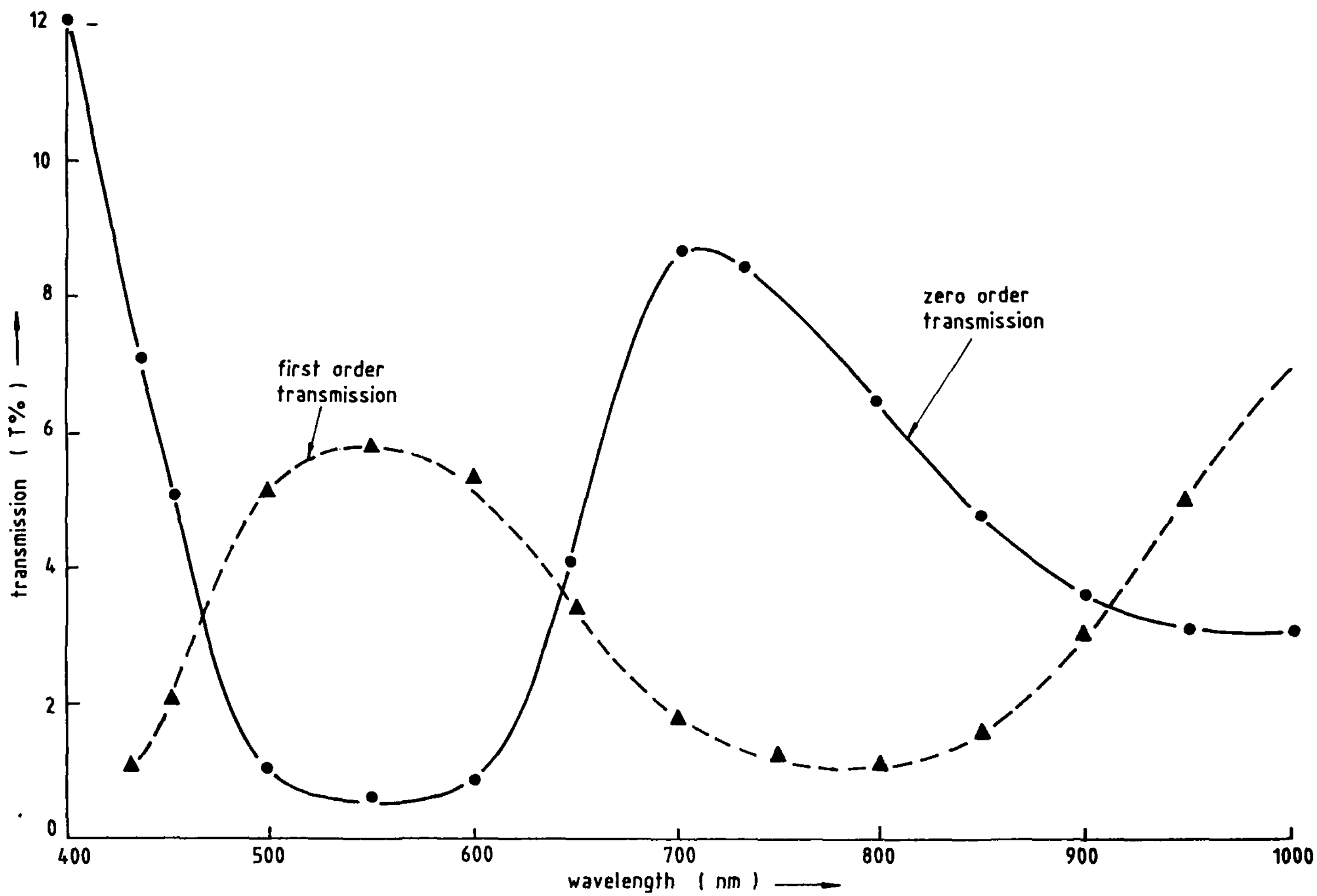

Figure 21. : Crossed sinusoidal photorisist grating11 on glass substrate, 600 lines / mm , groove depth ~ 896 nm (estimated).

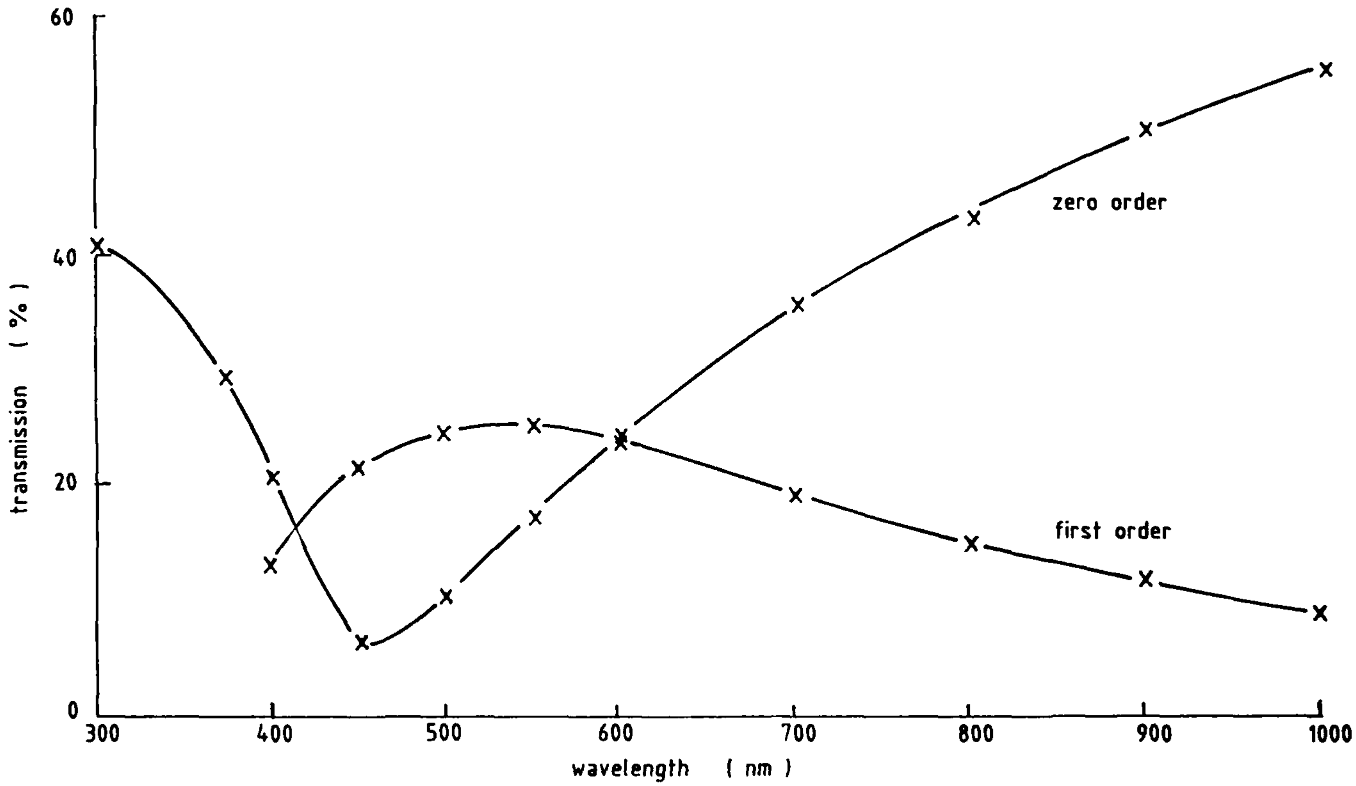

Figure 22. Normalized transmittance (%) / wavelength (nm) of grating 13 (Optometrics) of groove depth 537 nm.